ACCELERATED BRIDGE CONSTRUCTION (ABC) AND SEISMIC DAMAGE RESISTANT TECHNOLOGY: A NEW ZEALAND CHALLENGE

Alessandro Palermo[1] and Mustafa Mashal[2]

SUMMARY

Although New Zealand bridges performed well structurally during recent Canterbury earthquakes, some critical arterial routes lost their functionality. Life Safety is still our primary objective but nowadays we are moving towards new societal needs which also, at minimum, aim to limit business disruption. Building designers are already moving towards low-damage system technology for both structural and non-structural components. Bridge engineers have to inherit those enhanced concepts and technologies. In fact, in order to protect the economy and save lives, it is vital that bridges remain drivable after a natural disaster, such as an earthquake.

More importantly asset managers and networks' owners want rapid response, design flexibility, quick construction and limited maintenance costs. This should be possible to be achieved by contractors and designers with limited budgets. In very populated urban centres or a critical network location and moderate-to-high seismicity an Accelerated Bridge Construction (ABC) technology which combines durable materials and low-damage technology, seems to be the only viable solution to minimize traffic disruption during the bridge life.

The American Association of State Highway Transportation Officials (AASHTO) started in 2002 a long-term strategic bridge plan which aims to cover all these issues. Similar research strategy was initiated in Japan, Taiwan and Europe which is slowly going towards adaptation of ABC as a standard bridge practice. The question would be what is New Zealand vision for the next twenty-thirty years?

This paper aims to overview the current international trends and challenges and gives innovative concepts which can be contextualized for New Zealand bridges.

INTRODUCTION

Some of bridge structures which were constructed between 1920 to 1950 in New Zealand need major retrofitting and possible replacement because of their narrow width and poor approach highway alignment. The activities concerned with the maintenance, retrofitting and frequent inspection of these bridges can cause severe traffic congestion and disruption. We can extend the serviceability life of bridges to one hundred years with the intent to minimize maintenance costs through the improvement of materials and construction technologies. More importantly, during bridge life, natural hazards such as earthquakes may significantly impact on post-earthquake repairing strategies and therefore on the whole network. A clear example is the Canterbury earthquake which taught important lessons (Palermo et al. 2010). In fact, although no bridge collapse was recorded, some critical bridges lost their functionality causing traffic disruption to the city. A typical example is the bridge overpass at Moorhouse Avenue which remained closed for more than one month causing slowing of traffic.

The New Zealand Transportation Agency (NZTA, 2010) project "Roads of National Significance" (RoNS) identifies seven important state highways that are based around the five largest population centres in the country. These state highways are vital for the country's economic prosperity and require a considerable number of major new bridge structures. The Accelerated Bridge Construction (ABC) and Dissipative Controlled Rocking (DCR) technologies can be applied in construction of these bridges, especially in the urban areas.

We are moving towards new social targets which aim to limit business disruption to a minimum. Therefore, preserving the functionality of a bridge structure after a MCE (Maximum Credible Earthquake) event is a further objective that the research community is targeting (SEAOC 1995). In order to protect the economy and save lives, it is vital that bridges remain drivable after a natural disaster. Furthermore, since bridge structures are totally exposed to the environment, the community feels safe and less vulnerable if bridges preserve their integrity after a seismic event. A bridge structure links people but at the same time it embodies the advancements in civil engineering which will be clearly visible to every fellow citizen of the country.

Post-earthquake recovery of damaged bridges has resulted in significant traffic interruption to such an extent that communities cannot reliably plan their travel timing. Nowadays, the basic demand of communities is for durable and earthquake resilient infrastructures. Communities want long term resilient bridge infrastructure which minimizes maintenance costs during ordinary and extreme hazard conditions.

[1] *Senior lecturer, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch*

[2] *PhD candidate; Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch*

At the same time City Council asset managers and departments of transportation want quick response, flexibility and efficiency from contractors and designers with limited budgets. In a very populated urban centre or a particular location critical to the network, an Accelerated Bridge Construction (ABC) allows a reduction in construction time of up to 60-70% and therefore drastically minimises traffic disruption. Accelerated construction techniques, high performance durable materials and advanced earthquake technology are the success recipe for the next generation of bridges.

The research community has always been aware of the above mentioned challenges but nowadays, in some countries such as the United States, the research community, practitioners and end users are beginning to merge their expertise. For example, in 2002, the American Association of State Highway Transportation Officials (AASHTO) in collaboration with several research institutes and Universities started a strategic bridge plan which aims to improve the performance of bridges under different aspects (AASHTO strategic plan, 2005). One of the proposed solutions is to have more coordination and involvement of the research community with the Departments of Transportation (DOTs), contractors, and designers.

After this brief introduction, we may ask ourselves, what is the vision of the New Zealand bridge community for the next twenty-thirty years? Is it worth going towards ABC combined with long-term resilient materials and technologies?

The present paper will not specifically answer those questions, but it is evident that development of innovative technologies combined with high performance materials is not enough. A long term vision and strategy plan, which involves all parties, such as New Zealand Transportation Agency (NZTA), KiwiRail, key city councils (Auckland, Wellington, and Christchurch), contractors, practitioners and more importantly, the researchers needs to be synergistically developed.

This paper aims to give an overview of the current international trends and challenges, focusing on new innovative ideas in bridge engineering and contextualizing them into typical New Zealand functional requirements.

WHY ABC?

Cast-in-place substructures for bridges are the most commonly used technology regardless of the bridge dimensions (span lengths, pier heights). The use of cast-in place formwork for standard column shapes (circular or rectangular) is very cost effective. In the past, bridge precast components have been intended primarily for superstructure elements in bridges with short and moderate spans. These bridges support girders of I, T, U, and box sections. However, construction time of bridge substructures and the use of un-skilled labour can drastically impact on construction timeframe, causing further disruption and alteration to the business and the asset management of clients respectively.

Therefore, in the last two decades, primarily in the United States, DOTs (Freyermuth, 1999) promoted a total prefabrication of bridges (substructure and superstructure). A clear example is the Texas Department of Transportation which has been promoting the use of prefabricated bridge elements for years. Its intent is to reduce the impact of bridge construction on the traffic, especially in busy urban areas. Prefabricated construction also results in improved quality control associated with tolerances and material quality resulting in an increase in the durability and life of the bridge.

There are plenty of examples of precast piers and caps such as the Pierce Elevated Freeway Bridge Replacement project, and the Louetta Road Overpass (Billington et al 1999). The columns were segmentally precast and took only a short time to assemble on site. Other examples of precast concrete piers are Seven Mile Bridge, Sunshine Skyway Bridge, and John T. Collinson Rail Bridge in state of Florida, Vaina-Enon Bridge in state of Virginia, Linn Cove Viaduct, "Vail Pass" in state of Colorado, and the Texas State Highway 183 in Austin, Texas (Figure 1) and more recently, Victory Bridge in the state of New Jersey.

The latest construction technology for precast segmental box construction has been evolving and recent contributions presented by Billington et al. (2001) try to achieve a better standardization of the precast segmental substructure system in the United States which optimizes the shape of segments and construction sequence as shown in Figure 2. The advantages of ABC can be summarised as follow:

- Limited disruption to traffic while construction work is in progress, especially in populated areas
- Fast project delivery
- Cost savings related to the use of formwork
- More accuracy in bridge elements as they are prefabricated
- Better quality control of materials used in bridge elements
- Lowered machinery and equipment costs
- Higher durability
- Reduced weight of bridge structure
- Higher level of safety
- Minimized environmental impacts

Although ABC for bridge piers is becoming more popular in regions with low seismicity, voluble criticism and lack of confidence still appears if this technology can be applied in the earthquake prone areas.

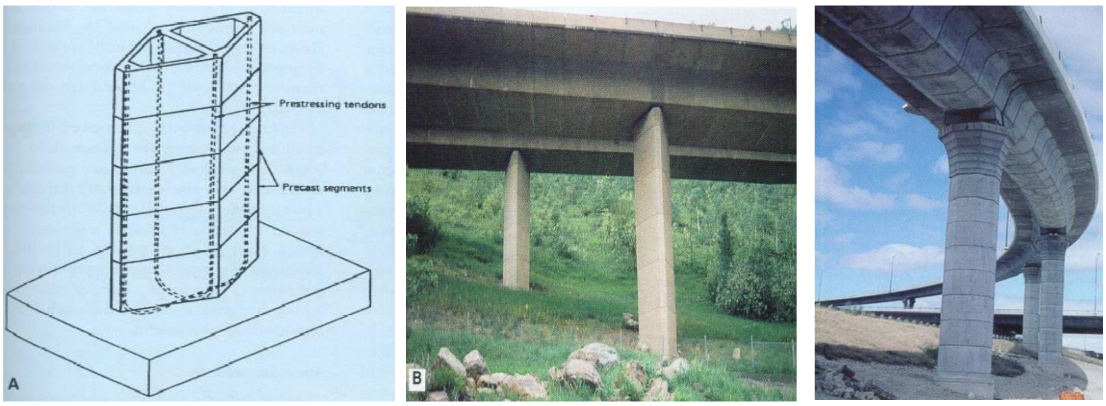


Figure 1: ***Precast segmental piers of the Vail Pass in Colorado (left & middle); Texas State Highway 183, Austin, Texas (right).***

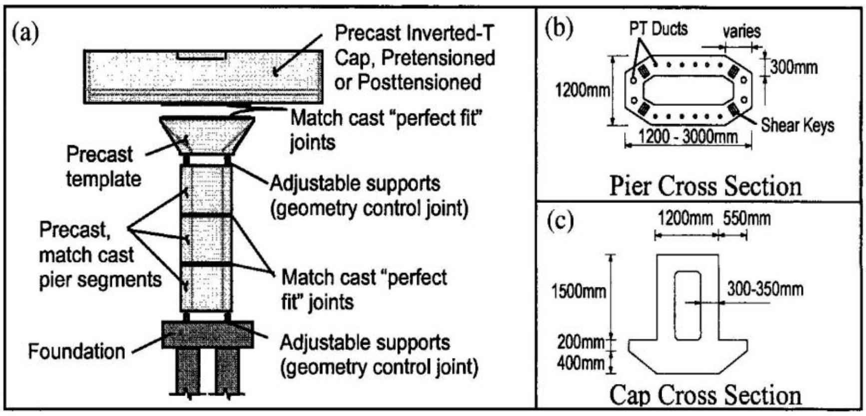


Figure 2: Elements of precast segmental Pier, after (Billington et al. 2011).

The earthquakes which occurred in 70s and 80s (Buckle 1994) highlighted unexpected high vulnerability of precast concrete structures in general. Deck unseating and deck-to-pier fastener connection failures were the main causes of bridge collapses. As a consequence, in Europe, new versions of standards penalised precast concrete structural systems through a more conservative reduction/ductility factor (Eurocode 8, 2004). Hence, one of the essential aspects of application of ABC in moderate-to-high seismicity areas is providing reliable connections for the prefabricated bridge elements. Having appropriate connections is important to develop the level of ductility needed in seismic prone areas.

For buildings, structural designers accepted the compromise to have partially prefabricated elements combined with cast-in-place joints, intending to emulate the real cast-in-place technology. This has the advantage of achieving the same ductility as for a cast-in-place structure while reducing construction time.

Nowadays civil engineering technologies are evolving towards "mechanized systems" which allocate most of the seismic demands to high-tech linkages or seismic devices. These "dissipative fuses" reduce the damage to the structural members which results in limited post-earthquake disruption.

Greater social demands and needs will slowly cause practitioners and contractors to abandon the concept of the emulative cast-in-place technology and migrate towards ABC incorporating dissipative connections which minimize damage to the members.

INTERNATIONAL TRENDS

The United States, Japan, Taiwan and European countries interpreted and developed Accelerated Bridge Construction in different ways. A brief summary of the overseas activities is reported in the following paragraphs.

United States

The roadway network in the United States is composed of 46,500 miles (74,800 km) of roadway. Following the rapid advancement of the transportation network in the second half of the twentieth century, the technology for innovative ideas of seismic-proof bridge design and construction has been changing its shape.

The California Department of Transportation (Caltrans) and AASHTO have a broad picture for improvement of ABC in their strategic plan (AASHTO strategic plan, 2005). Caltrans has adopted ABC as an element of Accelerated Project Delivery (APD), which has many benefits such as leading to expedited capital improvement, and improving the state's economy. The National Cooperative Highway Research Program (NCHRP) 20-73, Accelerating Transportation Programme and Project Delivery: Conception to Completion is one of the recently accomplished projects in the United States, (NCHRP 20-73, 2010). The NCHRP and a number of DOTs in the United States have been funding research projects to enhance the seismic performance of connections for ABC.

The NCHRP 12-74 project, Development of Precast Bent Caps for Seismic Regions, is a clear example of on-going

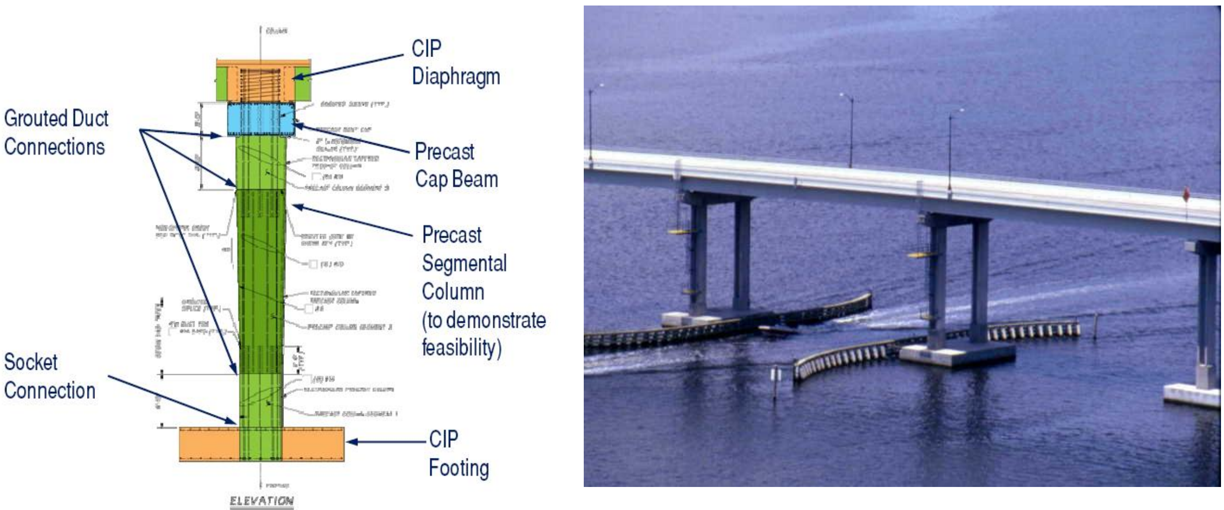


Figure 3: (Left) Highways for precast bent for seismic regions; (right) Edison Bridge, Florida, a fully prefabricated structure with grouted splice sleeve connection.

efforts for developing cap-to-column connection schemes. One of the complementary research works towards widespread implementation of ABC in high seismic zones is to investigate connections between column to foundation and girder to bent cap (TRB, 2010). At National level, there have been numerous workshops and reports on ABC recently such as:

- 2006 ABC Workshop, Reno, Nevada
- Precast/Prestressed Concrete Institute (PCI) Northeast Bridge Technical Committee (2006), "Guidelines for Accelerated Bridge Construction using Precast/Prestressed Concrete Components"
- Seismic ABC Meeting at 2007 Transportation Research Board (TRB) Annual Meeting
- 2007 Seismic ABC meeting in San Diego
- 2008 Federal Highway Administration (FHWA) ABC Conference in Baltimore, MD
- 2008 TRB Seismic Accelerated Bridge Construction (SABC) Collaboration Meetings
- Utah Department of Transportation (UDOT) ABC Standards Workshop report (2008)
- FHWA/Washington Department of Transportation ABC Workshop (September 2008)

This constant and frequent research lead to the production of useful documents such as FHWA – IF-09-10, (2010), which gives an overview of connection details for prefabricated bridge systems.

Caltrans is among the most active departments. It planned a strategic research plan for the next decade which is divided in two phases.

The first phase (Chung et al 2008) focuses on connections. They include foundation to substructure, substructure to superstructure, and other connection devices. The primary objective is to understand the seismic performance of existing ABC connections currently used in non seismic areas. In particular, research will be carried out on grouted splice sleeve connections (Figure 3 and 4 (left)), precast concrete or steel girder to integral cap joints using extended reinforcement and precast pile extension to precast bent cap connections. The solutions will be a sort of emulation of "cast in place" technology which accepts damage occurring in the plastic hinge zones of the pier. The research work at this phase is mainly to characterize the ultimate behaviour and performance of the aforementioned connections for severe earthquakes.

Grouted bar and splice sleeve couplers (Figure 4) are very popular. These type of connections are already in practice and currently available in the market. There are a number of benefits for using splice sleeve connections such as:

- They are manufactured by a number of companies and have already been used for building construction
- They can be used in areas with low to high seismicity
- They are suitable for prefabricated bridge elements
- The revision of guidelines, standards and specifications for these types of couplers does not appear a major issue

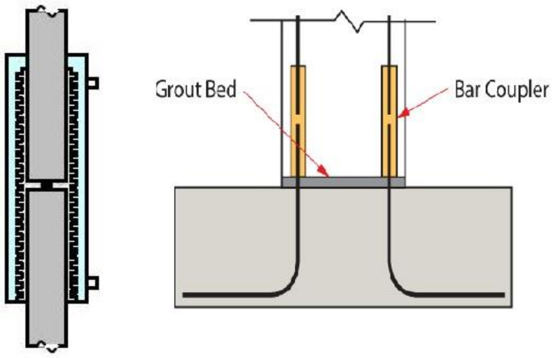


Figure 4: ***(Left) Grouted splice sleeve; (right) Grouted bar coupler connection aftar (NCHRP 698, 2011).***

The second phase of project focuses on structural systems incorporating low-damage technologies which minimize member damage through dissipating energy in the connections.

In last three years, ABC projects in California were completed in less than 5 months. As an example, the I-40 Marble Wash Bridge was replaced by precast girders and was completed in only 28 days (Figure 5). Caltrans is currently sponsoring workshops with consulting engineers, fabricators, erectors, transporters, and general contractors in order to engage the industries to improve construction cost and quality of new precast components and detailed solutions (Chang et al 2008). There are a number of ABC candidate bridges in the United States. The 1605/I10 Interchange Viaduct on San Benardino Freeway in California with a total length of 1000m, 16-spans (64-82m) and height of 9.1m is the next ABC project candidate.

Europe

The ABC in Europe doesn't have any innovative technology for bridge substructure in seismic areas. However, low-damage seismic protective systems are primarily based on seismic isolation of the bridge deck. This solution is growing exponentially and significant efforts have been put in order to make it cost competitive against traditional cast in place technology.

Figure 5: ***Replacement of I-40 Marble Wash Bridge with precast girders, (Caltrans, 2008) (left); precast bent cap in Conway Bypass (right), after (Thompson 2009).***

Figure 6: ***Prefabricated bridge elements; SPER bridge technology after (Ralls et al 2005).***

ABC is mainly limited to deck systems. The most common is the steel-composite deck with precast concrete panels (partial or full precast) connected through studs to the steel beam. Reduced time of construction and weight are the key reasons for the spreading of the technology.

Japan

Japan presents similar trends to Europe. Precast segmented bridge piers are not very popular; however only recently, Sumitomo Mitsui Construction Company developed a rapid construction system, named Sumitomo Precast form for resisting Earthquakes and for Rapid construction (SPER). It is a semi-prefabricated technology which allows a reduction in construction time of 60-70% with respect to cast in place technology. It consists of prefabricated panels with pre-inserted cross ties (Figure 6). The elements are stacked and fixed through epoxy joints. Concrete is then successively cast inside in order to form a solid section. The high performance concrete panels act as a sort of structural "shell" for the bridge pier and replace the formwork. A similar concept has been proposed and is under development in the United States at University at Buffalo (Bruneau & Marson, 2004) adopting a steel tube as structural shell instead of precast concrete panels.

Taiwan

There are several examples of segmental bridge columns in Taiwan. The Chang-Shou Bridge in Nan-Tou and Taichung Metro-Area No.4 Expressway are the examples of segmental bridge column construction in the country, (Figure 7).

The latest work by (Ou *et al*., 2012) proposes a new precast segmental concrete bridge column in seismic regions. The segmental column has lower region of the Cast-in-Place (CIP) construction. The height of the cast-in-place region is selected such that it simulates a conventional plastic hinge mechanism, (Figure 8, left and middle). Tests results have shown great ductility and energy dissipation capacities for the column by formation of the plastic hinge mechanism of the CIP region. A pushover analysis method was carried out for the proposed column to calibrate the experimental results, (Figure 8, right).

NEW ZEALAND CURRENT PRACTICE

Currently the state highway network in New Zealand includes about 11,000 kilometres of roads, more than 4000 bridges and a large number of culverts. The combined length of bridges on the state highway network is over 140 kilometres. Reinforced concrete bridges and culverts make up more than 80% of the combined length and almost 75% of bridges. Cast-in-place concrete is used twice as frequently as precast concrete but the use of precast concrete is constantly growing. In fact, most of the old existing reinforced concrete and timber bridges which were built in the 30s-50s after reaching the end of their service life are generally replaced with a precast concrete decking system. An example of where this occurs is Christchurch city as documented in "A City of Bridges" (Ince, John. A., 1998). Nowadays New Zealand bridges with small span length (15-30 m) are typically constructed with precast decking, which can be either continuous or simply supported with cast-in-place sub-structure (piers and foundations). If stringent function requirements lead to bridge span greater than 30 m, a reinforced concrete solution which adopts cantilevered or launched construction becomes the primary and preferred construction/design solution. Figure 9 (right) shows a typical example of bridge with precast bridge decking and cast-in-place piers. Bridge girders with I-sections are still the most popular (Figure 9, left) for moderate spans while duo-hollow core units are very efficient and cost effective if small spans are targeted, (Figure 10a); however, based on the recent NZTA Research Report 364. (2008), this trend might change in the future.

Bridge substructures are typically cast in place. Although, due to the market size, high technology facilities have not been developed for precast concrete piers, New Zealand practitioners feel confident to adopt cast-in-place piers accepting damage in the member and post-earthquake repair costs. The NZTA Bridge Manual (2003) indirectly drives the bridge practitioners towards cast-in-place solutions. In fact, it gives details on plastic hinge design in bridge piers (Figure 11) and briefly mentions advanced solutions (Section 5.5.8 for rocking foundation structures and Section. 5.5.9 for bridges adopting dissipative devices) which can be easily combined with ABC.

Figure 7: ***Segmental bridge columns in Taiwan; (left) Chang-Shou Bridge in Nan-Tou; (right) Taichung Metro-Area No.4 Expressway.***

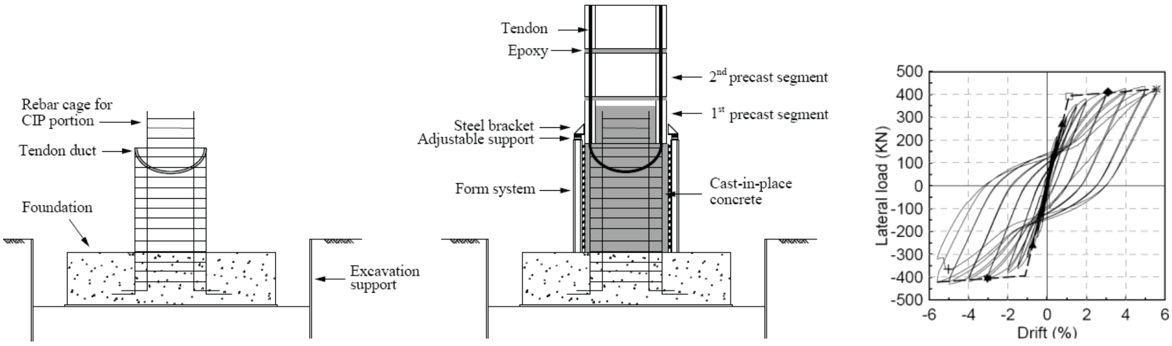


Figure 8: (Left and middle) joint construction of the CIP region; (right) hysteretic behaviour after (Ou et al., 2012).

SEISMIC DAMAGE RESISTANT TECHNOLOGIES

This section overviews past and recent research in the field of seismic low damage technologies for bridges at national and international level. Particular focus is also given to New Zealand in the 60s-80s where bridge engineering was flourishing.

New Zealand Pioneers

In the 70-80s, New Zealand was one of the pioneers for the application of the advanced seismic engineering technologies which incorporated concepts of dissipative connections to absorb kinematic energy induced by earthquakes. The idea of using mechanical devices as the weakest link of the structural capacity chain can be considered as a precursor for the next generation of structures. One of the pioneers was certainly Bill Robinson who invented the lead extrusion damper in 1970

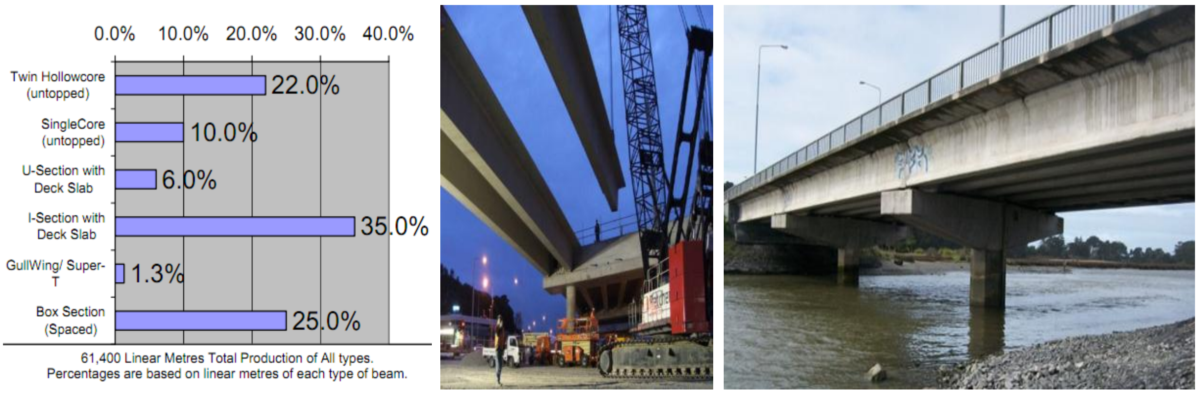
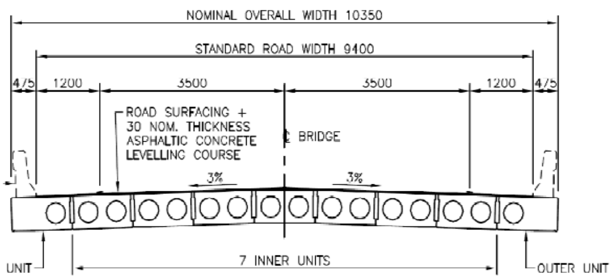
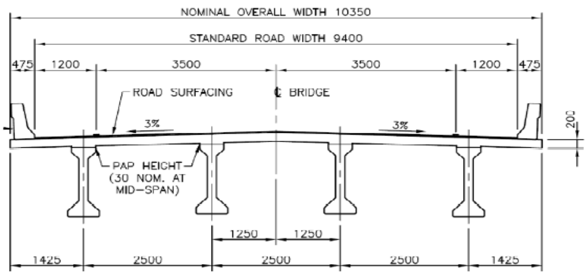


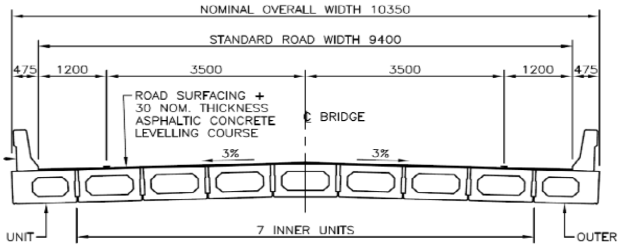
Figure 9: (Middle & right) New Zealand bridge examples; (left) summary of beam types produced after (Gray et al. 2003).



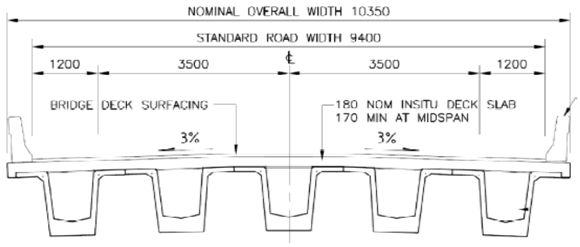
a) Duo Hollow Core section (up to 14m span length)



c) I section (up to 24m span length)



b) Hollow Core section (up to 22.5/25m span length)



d) Super T section (up to 30m span length)

Figure 10: Summary of beam types produced, after (NZTA, Report 364, 2008).

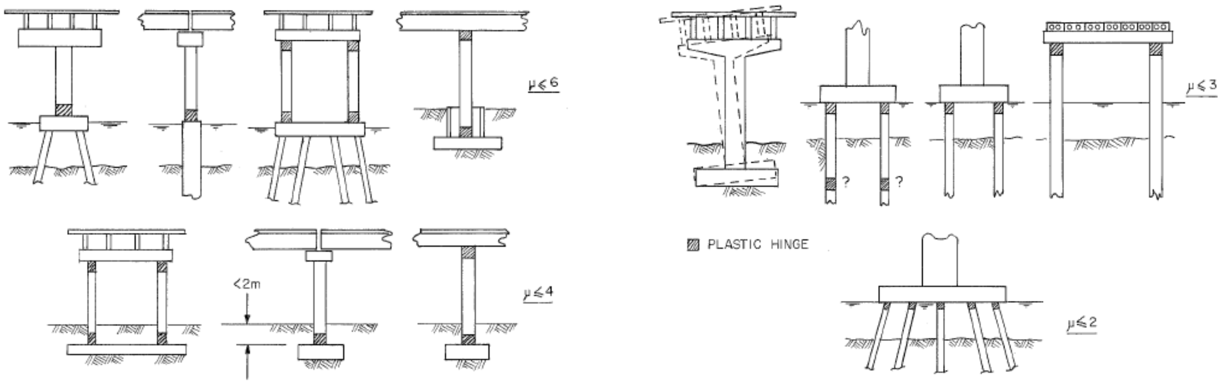
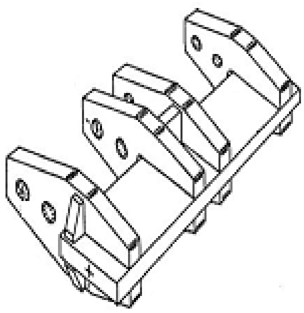


Figure 11: ***Location of plastic hinges and corresponding global displacement ductility factors, after (Bridge Manual 2003).***

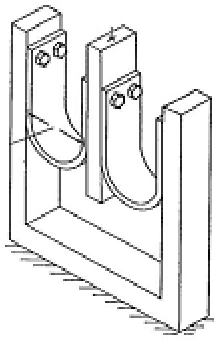
and lead-rubber bearing in 1974; after the occurrence of earthquakes in the United States (Northridge 1994) and Japan (Kobe 1995), the use of lead-rubber bearings use has tremendously increased. Another person who certainly contributed in this field is Ivan Skinner. Skinner's contributions included the development of innovative cost-efficient advanced devices/isolators and the implementation of these technologies into structural design (Skinner *et al.* 1993). The South Rangitikei viaduct which opened in 1981 is a clear example. It spans over the Rangitikei River and is the 4th highest railway viaduct in New Zealand, (also the 2nd longest viaduct in New Zealand), 78 m high and 315 m long. It is an impressive all-concrete structure with twin-shafted vertical piers carrying a continuous prestressed hollow box superstructure of six spans. The viaduct is an example of isolation through controlled base-uplift in a transverse rocking action. When an earthquake occurs, the pier bases can lift up to 130 mm to allow energy and pressure to shift from one pier leg to the other. The rocking action is controlled by large energy dissipaters installed in the pier bases. Figure 12a and 12b illustrate the steel torsional damper with transverse loading arms. Figure 12c, 12d, and 12e show other means of cost effective dissipaters in the bridge structures. U-strip and single axis dampers have already been used in buildings located in high seismic zones.

Seismic isolation and dissipative devices developed in the 70s and 80s are not extensively used in the current New Zealand bridge practice, (Figure 12f and 12g). Up to year 2005, 48 road bridges and one Railway bridge were seismically isolated (Kelly *et al.*, 2010) which corresponds to less than 1% of the bridge road network. These technologies might be favourably adopted if properly optimized in conjunction with ABC. The utilisation of ABC would result in low post-earthquake repair costs, minimized traffic disruption during construction and minimized maintenance costs.

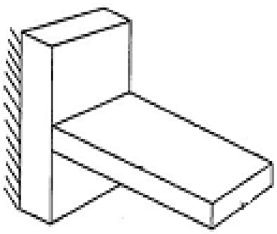
a) Rangitikei River Railway Viaduct (Rocking piers)



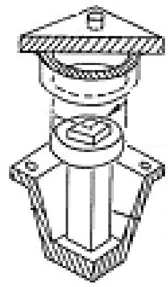
b) Torsional damper



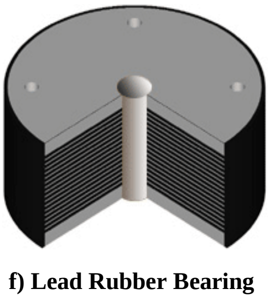
c) U-strips



d) Single axis damper



e) Flexural Beam



f) Lead Rubber Bearing

g) Friction Pendulum

Figure 12: ***Basic types of hysteretic dampers after (Skinner et al .1993).***

Recent International Research

For sake of brevity, technologies based on seismic isolation devices and pure foundation rocking are not overviewed in this paragraph. One of the best ways to limit damage in the pier is providing enough dissipation capacity in the connection, creating a sort of jointed ductile connection system (Stanton *et al.*, 1991). These connections can be easily activated by relative kinematic displacements/rotations between the structural members. Recent studies on buildings (Priestley *et al.,* 1999) proved that an efficient and viable solution is to allow the rocking motion between structural members, i.e. beam-to-column or wall-to-foundation. The rocking motion is "controlled" by an additional restoring force given by unbounded post-tensioned i.e. unbounded tendons or high strength steel bars and becomes more "dissipative" through the use of dissipative linkages (reinforcing bars or mechanical dissipative devices) placed at the rocking section. Therefore, the Dissipative Controlled Rocking (DCR) activates when an earthquake occurs, providing restoring or self-centering capacity plus dissipation. This technology allows reduction of the potential damage to the substructure and superstructure, while preserving the functionality of the bridge after the earthquake. The only sacrificial elements are the dissipative devices which can be easily replaced.

(2004). However in the late 80s, Mander and Chen (1997) implemented similar concepts of dissipative rocking bridge piers on rubber pads. Further studies in the United States (such as Priestley & Calvi 2002, Ou *et al.,* 2007, Yen & Aref 2010) followed with the investigation of single post-tensioned segmented bridge piers with and without supplemental dissipation devices. Results from this research demonstrated that DCR technology can drastically limit the damage in the pier, limiting the dissipation capacity in one or more critical rocking regions.

Recently, researchers at the State University of New York at Buffalo/MCEER, as part of the above mentioned ABC programme in the United States have successfully tested a half scale fully precast segmental bridge (Figure 14) subjected to an earthquake of magnitude 7.0 Richter.

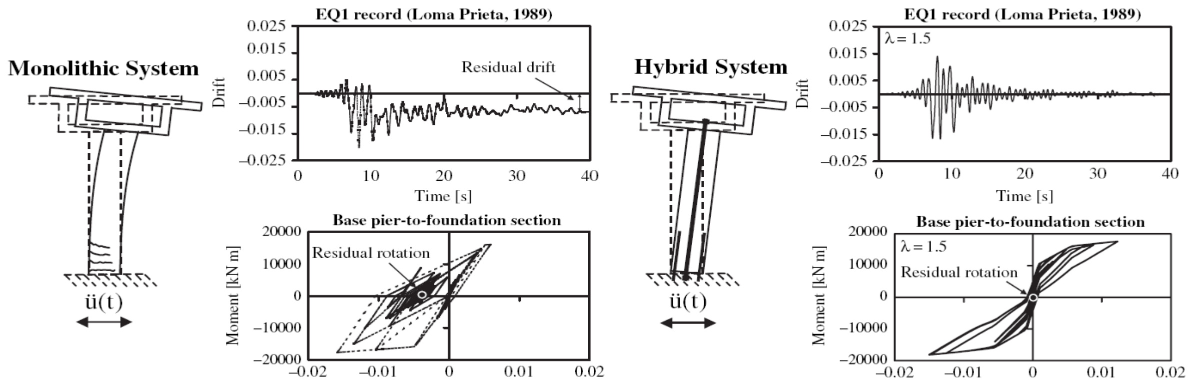


***Figure 13:** Comparison of seismic response of the bridge piers for the hybrid & monolithic connections under Loma Prieta earthquake (EQ1), after Palermo 2008.*

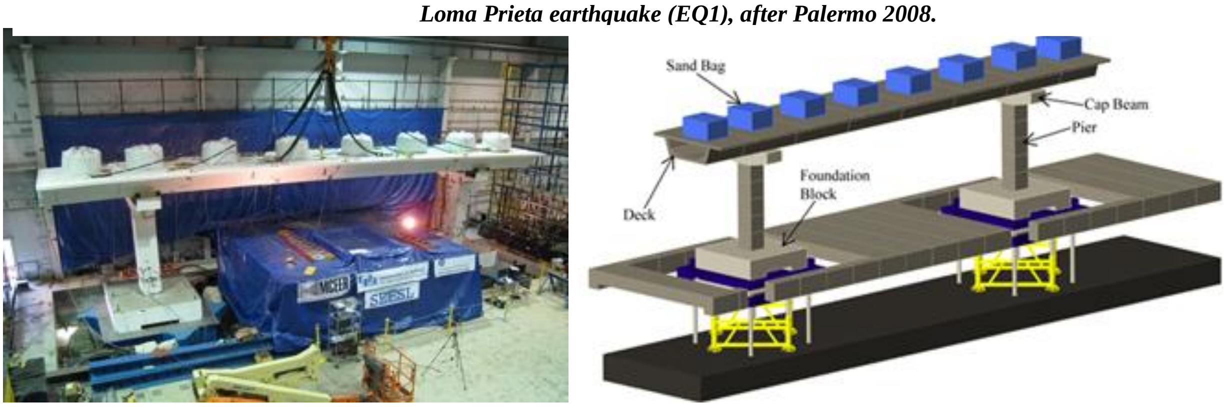


***Figure 14:** Half-scale post-tensioned segmented bridge system, after (Sideris et al 2010).*

The Kobe earthquake (1995) showed that the self-centering capacity can be an important design consideration to preserve the structural integrity of a bridge. In fact, several bridge piers, despite perfect compliancy with the current design standards, suffered extensive damage with large permanent displacements/drifts beyond the reparability limit. Japanese scientists believed that the use of post-tensioning, (Kawashima 2002) could be an efficient way to drastically reduce the residual permanent drift in the bridge piers. As a consequence, the Japanese Seismic Code introduced an additional check on residual drift. To highlight benefits of this technology, Figure 13 shows the advantages of a controlled rocking solution when compared with a traditional monolithic bridge pier. Both systems are designed with the same moment capacity. For the rocking system there is no damage of the structural member with similar maximum displacements as the monolithic member but zero residual permanent displacements/drift.

The PRESSS programme (Priestley *et al.,* 1999) implemented this concept for frame and wall systems; the extension of this concept to bridges was successively studied by Palermo

The bridge remained functional with no structural damage after going under three shake table tests in both vertical and horizontal directions, (Sideris *et al.,* 2010). The system didn't incorporate any supplemental source of dissipation but relied on multi-rocking response and sliding friction between precast pier segments.

SEISMIC RESISTANT TECHNOLOGIES AND ACCELERATED BRIDGE CONSTRUCTION: FUTURE RESEARCH AND DESIGN CONCEPTS FOR SHORT-MEDIUM SPAN NEW ZEALAND BRIDGES

The New Zealand bridge engineering community has the competence and the structure to implement ABC for substructures incorporating advanced low damage technologies (rocking and/or seismic isolation based) (Figure 15). Based on the New Zealand market trend, damage resistant bridge construction should mainly target low-medium span bridges (30 m maximum span) and then expand alternative construction systems for medium-long span bridges. Similar to

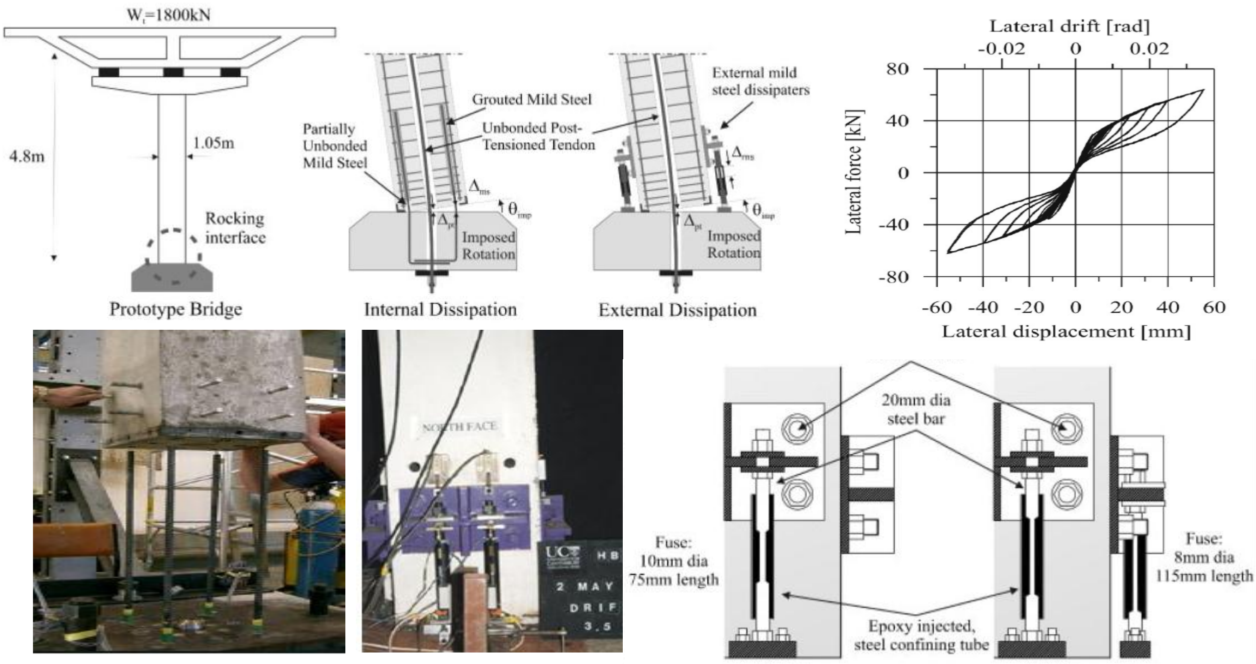


Figure 15: ***Controlled rocking concept (top-left); solution with internal reinforcing steel (bottom-left); solution with external dissipation device (bottom-right); test results for solution with external dissipaters (Top-right), after (Marriott, 2009).***

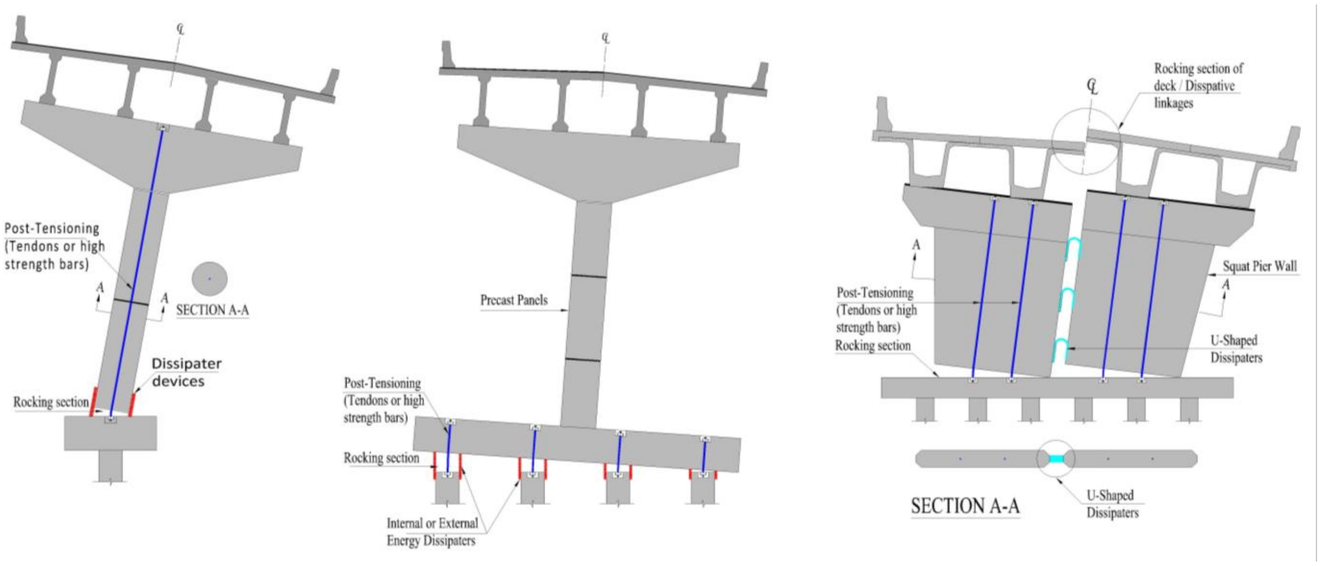


Figure 16: ***Controlled rocking of damage resistant bridge construction substructure: pier-to-foundation (left); foundation-to-piles (middle); coupled rocking pier-to-foundation (right).***

the precast decking solutions (NZTA, 2008) recently supported by NZTA, suitable precast segmental bridge substructure systems need to be identified for different bridge span length, construction limits (e.g. maximum cost-effective crane limit) and functional requirements. For each deck system typology, different configurations of bridge substructures, such as mono or multiple piers bent, need to be identified as well as the location of dissipative rocking sections. For example, Figure 16 (left) considers dissipative rocking at the pier-to-foundation interface while the system of Figure 16 (middle) introduces dissipative rocking at the foundation to piles interface. The latter can be implemented similar to the Rangitikei stepping Railway Bridge; it has the advantage of having more rocking sections, corresponding to each foundation-to-pile section, which all contribute to dissipate energy. If functional requirements (e.g. limitation of pier transverse section and high axial load) force the designer to use squat wall piers, Figure 16 (right) is an example of viable design solutions. The bridge substructure system consisted of post-tensioned rocking walls coupled through dissipative U-Shaped Flexural Plates (UFP) devices (Figure 17), (Iqbal *et al.*, 2010, Skinner *et al.*, 1993). During an earthquake, the dissipative devices are activated by the vertical relative sliding of the precast concrete walls which occurs during their rocking motion.

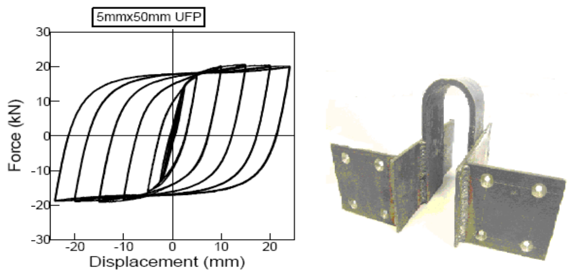


Figure 17: ***UFP dissipaters after (Iqbal 2010).***

All the previous solutions had dissipative rocking motion occurring in the bridge substructure. However, damage resistant bridge construction might also be designed combining precast post-tensioned bridge deck elements with dissipative linkages. They can be either traditional seismic isolators, or dissipative linkages. The former can be opportunely optimised within a rocking post-tensioned bridge substructure in order to guarantee adequate balance of dissipation and self-centering capacity. The latter are inserted in the segmented bridge deck and activated by the relative transverse rotation at the bridge deck joints. Existing linkages currently adopted in the retrofit programme (Chapman *et al.*, 2005) (Figure 18) can be slightly modified for this purpose.

***Figure 18:** Example of linkages in the girders.*

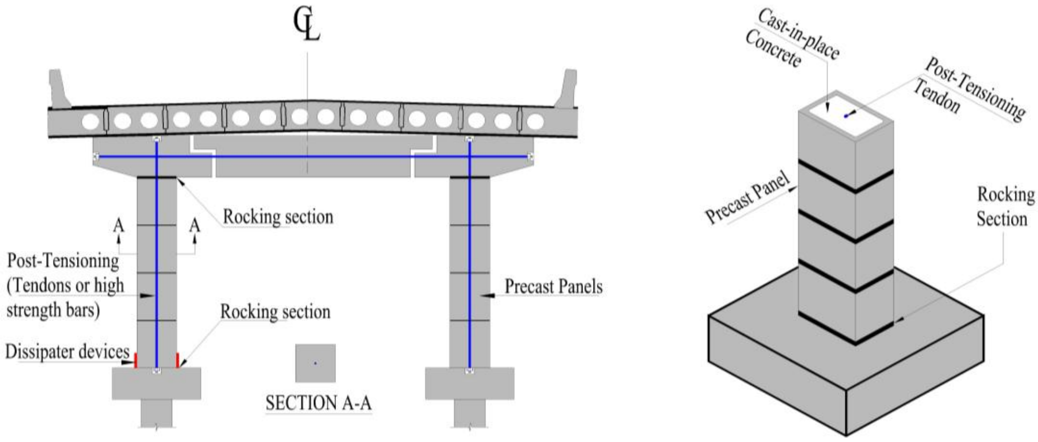


***Figure 19:** Controlled rocking of damage resistant bridge construction substructure: SPER rocking bridge pier (left); post-tensioned bridge substructure (right).*

Figure 19 shows preliminary concept which needs to be properly detailed for each precast concrete deck. It presents an example of modified SPER technology with unbounded post-tensioning. This system can be either implemented for mono (Figure 19, right) or multi bridge pier bent (Figure 19, left).

Force or displacement based design methods need to incorporate all above mentioned features including the effects of soil-structure interaction. Design and construction has also to consider interaction with non-structural components, i.e. approaches, balustrades, pipes etc. Following the recent Canterbury earthquakes (Palermo *et al.*, 2010), it was learnt that an extremely high disruption cost can be associated with the services such as sewage/water pipes, power cables etc.

Another crucial aspect is to guarantee long-term resilience of the structure and this can be achieved through a proper selection of durable materials with enhanced mechanical properties and appropriate detailing. For example, ultra-high and high performance concrete can drastically drop cost of construction, while GFRP (Glass Fiber Reinforced Polymer), CFRP (Carbon Fiber Reinforced Polymer) or stainless steel post-tensioning can reduce the frequency of inspections and therefore the overall maintenance costs. Long-term resilience can be achieved providing sufficient cover, use of steel protective plates, and coating.

CONCLUSIONS AND DISCUSSION

The paper provides a brief overview of international trends of Seismic Accelerated Bridge Construction (ABC). The United States through FHWA, Caltrans and AASHTO seems to strongly believe in the benefits of ABC and therefore a massive collaborative programme has been on-going for 6-8 years. The researchers in the United States are currently working on new ways of improving the seismic performance of ABC bridges looking at both emulative cast in place and low damage controlled rocking solutions.

New Zealand has always been a world leader for pioneering design concepts in earthquake engineering. The research work carried by (Park and Paulay, 1976) have been a revolutionary step in earthquake design, which immediately and beneficially impacted New Zealand bridge engineering standards, construction and design.

Despite living a flourishing past, the amount of research in the field of bridge engineering has significantly decreased over the past 10 to 15 years as also mentioned by Kotze (2009). The New Zealand bridge community seems to live in the legacy of the past and a strategic research vision for the next two decades is still missing.

Technologies evolve based on social needs and can strongly impact only if research, profession and DOTs are constantly linked.

The recently funded long term (2011-2015) project from the Ministry of Science – Natural Hazard Platform "Advanced Bridge Construction and Design for New Zealand (ABCD – NZ Bridges)" which is coordinated by the University of Canterbury can be the starting point for the development of the next generation of bridge systems.

Those advanced technologies will meet the higher expectations of our society, but they will effectively impact in our bridge community only if NZTA, KiwiRail and key bridge practitioners are constantly interacting with researchers involved in the research programme.

ACKNOWLEDGMENTS

Authors wish to acknowledge Geoff Leech, technical manager of Robinson Ltd for supplying useful data and Samuel White, Master student at University of Canterbury for support in paper editing. A special mention also goes to Associate Professor Stefano Pampanin, Dr. Dion Mariott who extensively contributed to the development of technical

solutions and refinement of design procedures, especially for building systems.

REFERENCES

1 Ou, Y.C, Tsai, M.S., Oktavianus, Y. and Chang, K.C. (2012). "Cyclic testing of a tall precast segmental concrete bridge column with a cast-in-place plastic hinge region". *6th International Conference on Bridge Maintenance, Safety, and Management (IABMAS).* July 8-12 2012 , Stresa, Italy.

2 Marsh, M.L., Stanton, J.F. (2011). "Application of Accelerated Bridge Construction Connections in Moderate-to-High Seismic Regions". NCHRP Report 698, *Transportation Research Board.* Washington, D.C., United States.

3 Transportation Research Board (TRB) (2010). " Advancement of Accelerated Bridge Construction (ABC) in Moderate-to-High Seismic Regions". *Transportation Research Board.* Washington, D.C., United States.

4 FHWA – IF-09-10 (2010). "Connection Details for Prefabricated Bridge Elements and Systems". *Federal Highway Administration.* United States.

5 Iqbal, A., Pampanin, S., Palermo, A., Buchanan, A. (2010). "Seismic response of post-tensioned timber walls". *14th European Conference on Earthquake Engineering.* Skopie-Ohrid, Republic of Macedonia, August 30 – September 3rd 2010, submitted and accepted, pp. 10.

6 Kelly, T., Skinner, I., Robinson, W.H. (2010). "Seismic Isolation for Designers and Structural Engineers". *National Information Centre of Earthquake Engineering (NICEE).* ISBN 978-81-960130-6-4.

7 NCHRP 20-73 (2010). "Accelerating Transportation Program and Project Delivery: Conception to Completion". *Transportation Research Board (TRB).* Washington, D.C., United States.

8 Sideris, P., Anagnostopoulou, M., Aref, A., Filiatrault, A. (2010). "Seismic performance of precast segmental bridges". *9th US National and 10th Canadian Conference on Earthquake Engineering: Reaching Beyond Borders.* July 25-29, Toronto, Canada.

9 Palermo, A., Heux, M.L., Bruneau, M., Anagnostopoulou, M., Wotherspoon, L., and Hogan, L. (2010). "Preliminary findings on performance of bridges in the 2010 darfield earthquake" *Bulletin of the New Zealand Society for Earthquake Engineering.* **43** (4), 412-420.

10 Yen, W.P., Aref, A. (2010). "Development of Accelerated Bridge Construction Detail for Seismic Regions". *State University of New York at Buffalo.* New York, United States.

11 Kotze, R. (2009). " The Future of Concrete Bridges". *Contrafed.* Vol.**33**, No.1, New Zealand.

12 Marriott, D., Pampanin, S., Palermo, A. (2009). "Quasi-static and pseudo-dynamic tests of unbounded post-tensioned rocking bridge piers with external dissipation devices". *Earthquake Engineering and Structural Dynamics.* Vol. **38** (3), pp. 331-354.

13 Marriott, D. (2009). "The Development of High-Performance Post-Tensioned Rocking Systems for the Seismic Design of Structures". PhD thesis, *University of Canterbury*, Christchurch, New Zealand.

14 Thompson, K. (2009). "AASHTO and Caltrans Research Programme Overview". *California Department of Transportation,* California. United States.

15 Chung, P.C., Wolfe, R.W., Fang, J.Q. (2008). "Caltrans Accelerated Bridge Construction (ABC) Initiative". *California Department of Transportation*. California, United Sates.

16 NZTA (2008) "Standard Precast Concrete Bridge Beams". *NZTA* .Research Report 364.

17 Palermo, A., Marriott, D., Pampanin, S. (2007). "Design, modelling, and experimental response of seismic resistant bridge piers with posttensioned dissipating connections". *Journal of Structural Engineering (ASCE).* Vol. **133** (11), November, 1st, pp. 1-14.

18 Ou, Y.C., Chiewanichakorn, M., Aref, A.J., Lee, G.C. (2007). "Seismic performance of segmental precast unbounded posttensioned concrete bridge columns". *Journal of Structural Engineering.* Vol. **133**, No. 11, November.

19 AASHTO Highway Subcommittee on Bridges and Structures (2005). "AASHTO Strategic Plan for Bridge Engineering". Washington, D.C., United States.

20 Chapman, H.E., Lauder, M.K., Wood, J. (2005). "Seismic Assessment and Retrofitting of New Zealand State Highway Bridges". *Proc. of the New Zealand Society Earthquake Engineering Conference (NZEES).* March, 11-13, Wairakei , New Zealand.

21 Ralls, M.L., Tang, B., Bhide, S., Brecto, B., Calvert, E., Capers, H., Dorgan, D., Matsumoto, E., Napier, C., Nickas, W., Russell, H. (2005). "Prefabricated Bridge Elements and Systems in Japan and Europe". *Federal Highway Administration,* FHWA-PL-05-003, March. United States.

22 Bruneau, M., Marson, J. (2004). "Seismic design of concrete-filled circular steel bridge piers". *Journal of Bridge Engineering.* **9**(1), 24-34.

23 Eurocode 8 (2004). "Design of Structures for Earthquake Resistance".

24 Palermo, A. (2004). "The use of controlled rocking in the seismic design of bridges". Ph.D. thesis, Structural Engineering Dept., Technical University of Milan, Italy.

25 Bridge Manual (2003). "Second Edition". *New Zealand Transportation Agency (NZTA).*

26 Gray, A., Gaby, P., Brown, G., Kirkcaldie, D., Cato, R., Sweetman, P. (2003). "New Zealand Precast Concrete Bridge Beams-Stage 1". *Transfund New Zealand Research Report.*

27 Kawashima, K. (2002). "Seismic design of concrete bridges". *Proc. of the first fib Congress.* Osaka, Japan.

28 Priestley, M.J.N., Calvi, G.M. (2002). "Strategies for repair and seismic upgrading of Bolu Viaduct 1, Turkey", *JEE.* Vol. **6**, No. Special Issue 1, pp. 157-184.

29 Billington, S.L., Barnes, R.W., Breen, J.E. (2001). "Alternative substructure systems for standard highway bridges". *ASCE Journal of Bridge Engineering.* Vol. **6**, No. 2, pp. 87-94.

30 Billington, S.L., Barnes, R.W., Breen, J.E. (1999). "A precast segmental substructure system for standard bridges". *PCI Journal.* Vol. **44**, No. 4, pp. 56-73.

31 Freyermuth, C.L. (1999). “Ten years of segmental achievements and projections for the next century”. *PCI Journal.* Vol. **44**, No. 3, pp. 36-52.

32 Priestley, M.J.N., Sritharan, S., Conley, J.R., Pampanin, S. (1999). “Preliminary results and conclusions from the PRESSS five-story precast concrete test-building”. *PCI Journal*. **44**(6), 42-67.

33 Ince, J. A. (1998). “A City of Bridges”. *Christchurch City Council.* Christchurch, New Zealand.

34 Mander, J.B., Chen, C.T. (1997). “Seismic Resistance of Bridge Piers Based on Damage Avoidance Design”. *Technical Report NCEER-97-0014 (National Centre for Earth. Eng. Research).* State University of New York, Buffalo.

35 SEAOC Vision 2000 Committee (1995). “ Performance-Based Seismic Engineering”. *Report prepared by Structural Engineers Association of California.* Sacramento, California.

36 Buckle, I.G. (1994). “The Northridge, California Earthquake of January 17, 1994: Performance of Highway Bridges”. *Technical Report NCEER-94-0008.*

37 Skinner, I., Robinson, W.H., McVerry, G.H. (1993). “An Introduction to Seismic Isolation”. *John Wiley & Sons*, New York.

38 Stanton, J.F., Hicks, T.R., Hawkins, N.M. (1991). "PRESSS Project 1.3 - Connection Classification and Evaluation". *PCI Journal.* **36**(5), Sept.-Oct., pp. 62-71.

39 McManus, K.J. (1980). “The Seismic Response of Bridge Structures Free to Rock on Their Foundations”. Master thesis, Civil Engineering Dept., University of Canterbury, Christchurch, New Zealand.

40 Priestley, M.J.N., Evison, R.J., Carr, A. (1978). “The seismic response of structures free to rock on their foundations”. *Bulletin of the New Zealand Society for Earthquake Engineering*. **11**(3), 141-150.

41 Park, R. and Paulay, T. (1976). “Reinforced Concrete Structures” Wiley, 800pp.